The Potential for Ocean Prediction and the Role of Altimeter Data

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Abstract A skillful ocean ~~forecasting~~ and capability will depend on ~~(1)~~ adequate data input, ~~(2) adequate~~ computing power, and ~~(3)~~ properly designed and adequately validated ocean models for data assimilation and forecasting. Once these conditions are satisfied, which is feasible with existing technology, forecasts of meandering currents and eddies up to a few months appear to be a reasonable expectation. Simulation studies suggest that the prediction of meandering currents and eddies requires high horizontal resolution (≈10 km), but only low vertical resolution. approx. High vertical resolution can be obtained by using the circulation model to provide horizontal and vertical advection to a grid of one-dimensional mixed-layer models. Circulation models on subdomains of major ocean basins with extensive open ocean boundaries require accurate boundary information at all levels in the vertical and for the duration of forecasts longer than a few days. Basin-scale models appear to be the most promising source for this information. To provide useful boundary conditions, the basin-scale models must also resolve the meandering currents and eddies. Class 7 computers (≈1 gigaflop and 32–128 million words), expected on the market in the ~~middle and late~~ 1980s, are required for eddy-resolving models of major ocean basins. Currently, satellites and atmospheric models provide the only

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prospects for oceanographic data and forcing functions with *global* coverage and resolution adequate for ocean circulation prediction models. For this purpose the most useful fields potentially available from satellites are current-related variations in the sea-surface elevation derived from altimeter data and scatterometer-derived wind stress. Choosing an appropriate altimeter track pattern is critical. Successful ocean prediction appears feasible without extensive subsurface data acquisition by using the circulation model to convert the potentially well-observed fields at the surface into subsurface information. This looks more promising than attempting to assimilate the extremely sparse subsurface data. Where adequate subsurface data are available (nowhere at present), they should, of course, be used. Subsurface data and major field programs are vital for local and regional subsurface validation of the forecast models, but altimeter data are essential for *global* prediction and representation of individual current meanders and eddies. Otherwise, in most regions it would be necessary to rely on the simulation skill of the model and the forcing functions, which are only weakly coupled to many of these oceanographic features. Within the next decade the appropriate satellite data, Class 7 computers, and eddy-resolving basin or global-scale models should become available, and should be used to form the heart of a global ocean prediction system. Part of this paper outlines a strategy for global ocean prediction based on these elements and on plans at the Naval Ocean Research and Development Activity.

Introduction

The next decade should be to numerical prediction of ocean circulation what the 1950s and 1960s were to numerical weather prediction: a time when the essential elements came together to permit major advances. These elements are (1) adequate data input, (2) adequate computing power, and (3) properly designed and adequately validated models for both data assimilation and forecasting. Ten years ago none of these requirements were satisfied for many aspects of ocean forecasting. Meandering currents and eddies provide a notable example: clear prospects for adequate data with high density and global coverage from sat-

ellite-borne instruments have become evident only in the last few years; Class 7 computers with a sustainable speed of ~1 gigaflop and 32 to 128 millions words of memory are required for eddy-resolving forecasts in major ocean basins; and notable differences from meteorology are required in model design and in data assimilation.

The U.S. Navy has determined a requirement for an ocean prediction capability, and has established a research program to meet the requirement. This paper addresses the requirements for data and computing power and the issues of model design and data assimilation, primarily in the context of the Navy effort at the Naval Ocean Research and Development Activity (NORDA); it is, however, an overview and not a report on any specific research project. It should be stressed that there are many types of ocean prediction, aimed at different aspects of the motion, internal structure, and surface of the ocean. This paper is focused on one important aspect where altimeter data can play a central role. In particular, the role that satellite altimeter data can play will be demonstrated for detailed surface and subsurface forecasts of meandering currents, eddies, and frontal locations, forecasts that may extend up to several months.

Different Types of Ocean Prediction

Before concentrating on a particular type of ocean prediction, we will briefly survey the range of ocean phenomena for which forecasts are desirable. If we focus on a particular region of the ocean, then the evolution of the motion, internal structure, and surface from time t_0 to time t_1 depends on (1) the initial state at t_0, (2) the atmospheric, astronomical, and geological forcing functions, (3) flow through any open boundary segments of the region, (4) the bottom topography and coastline geometry, and (5) the physical and dynamic properties of the ocean fluid. The ocean exhibits a wide variety of phenomena on a broad spectrum of time and space scales that differ greatly in their manner and degree of dependence on each of these factors. Thus in predicting different phenomena we anticipate (1) different degrees of ac-

curacy in the initial state, (2) different time scales for accurate forecasts, (3) different modeling strategies, (4) different data requirements, and (5) different data acquisition and sampling strategies. Also, note that these five aspects can depend on interactions between phenomena, time and space scales, and, of course, the adequacy of the models and the data input. Fortunately, many phenomena and scales are sufficiently decoupled that it is possible to design forecast models that can simulate and forecast certain phenomena while suppressing or parameterizing the statistical effects of the remainder.

Table 1 shows some useful categories of oceanic response to atmospheric forcing that cover many phenomena of potential interest in ocean forecasting. It is not all-encompassing (e.g., tides, tsunamis, individual salt fingers, and convection cells are omitted), but is intended to help place the multifaceted problem of ocean forecasting into perspective, identify phenomena where predictive skill is feasible, clarify the potential roles of altimeter data, and define the focus of the paper, which is primarily on Class 2 as defined in the table.

"Nowcasting" is important in all three classes listed in Table 1. To nowcast, the models are integrated forward in time while being driven by new atmospheric forcing functions and assimilating appropriate new oceanic data as they become available. This allows the models to fill in temporal gaps in the data by using their predictive skill, convert better-observed surface fields into subsurface structure, and convert better-observed atmospheric forcing functions into oceanographic information.

Up until now, ocean forecasting efforts have concentrated primarily on tides and certain phenomena in Class 1, a class which to some extent includes the cumulative effects of fine scale phenomena predicted by empirical or semiempirical parameterizations. The U.S. Navy has recently initiated hemispheric numerical forecasts of the upper mixed layer at the Fleet Numerical Oceanography Center (Clancy and Martin, 1981; Clancy and Pollak, 1983). It has also installed a hemispheric surface wave forecast model (Pierson, 1982). Among ocean phenomena, numerical storm surge prediction has a relatively long history (Welander,

1961; Jelesnianski, 1967; Crawford, 1979). Coastal upwelling has been the subject of a few hindcasting studies (Heburn, 1980).

Although a satellite altimeter can measure surface wind speed and significant wave height in addition to sea-surface elevation (Fedor and Brown, 1982), the value of a single altimeter with only a nadir beam is severely degraded when applied to prediction of phenomena in Class 1. This is due to the inverse relation between spatial and temporal resolution, which prevents adequate resolution for these phenomena in both space and time simultaneously. This is also true for tsunamis, which have time scales of a few hours (Neumann and Pierson, 1966). However, the altimeter can be useful in constructing climatologies of wind speed and significant wave height (Chelton et al., 1981; Wentz et al., 1982; Mognard et al., 1983), in validation and tuning of certain Class 1 forecast models, and in some research problems involving these quantities. Because tides are repetitive with known periods, the altimeter should be important in refining the global knowledge of tidal phase and amplitude (Cartwright and Alcock, 1981; Brown and Hutchinson, 1981; Diamante and Nee, 1981; Mazzega, 1983).

The output from atmospheric prediction models and satellite-borne instruments measuring surface wind speed and direction (scatterometers) or even wind speed alone (scanning multifrequency microwave radiometers [SMMRs]) shows great promise in facilitating predictions in Class 1. Scatterometers and microwave radiometers can provide adequate coverage, accuracy, and spatial and temporal resolution, except for coverage near coastal boundaries (Jones et al., 1982; Wentz et al., 1982; Lipes, 1982; Satellite Surface Stress Working Group, 1982; Mueller, 1982). For mixed-layer forecasting, measurements of sea-surface temperature (SST) (multichannel infrared and microwave radiometers) would also be of value. However, SST measurements remain plagued by cloud contamination (infared radiometers) or relatively poor accuracy and resolution (SMMR, 125 km at 6.6 GHz with 1-m diameter antenna; 25 km at 6.6 GHz with the 4-m diameter parabolic dish antenna proposed for the canceled National Oceanic Satellite System, NOSS) (Mueller, 1982). Res-

Table 1
Classes of Oceanic Response to Atmospheric Forcing where Predictive Skill Is Feasible

Class	Implications	Examples
1. Strong, rapid (<1 week) and direct	A. short-range forecasts limited by the time scale for atmospheric predictive skill B. less sensitive to errors in the initial state; more sensitive to errors in the forcing functions	surface mixed layers, surface and some internal waves, Ekman drift currents, some coastal and equatorial processes such as upwelling (in some cases), coastal storm surges, and the onset of some equatorial and coastal waves
2. Slow (weeks to months) and indirect	A. long-range forecasts (potentially a month or more) B. more sensitive to errors in the initial state; less sensitive to errors in the forcing functions C. statistical properties of features and ensembles may be predicted by skillful simulation D. prediction of individual features requires oceanographic data; altimeter data are the most promising operational source now on the horizon	mesoscale eddies, meandering currents, associated frontal positions, features caused by mesoscale flow instabilities

3. Slow (weeks to years) but direct (i.e. integrated response)	A. long-range forecasts B. sensitive to errors in atmospheric forcing functions on long time scales (e.g. monthly means), but less sensitive to errors on short time scales (e.g. daily fluctuations) C. nowcasting and forecasting are potentially feasible without good oceanic data by means of simulations that use appropriate ocean circulation models	El Nino, much of the tropical ocean circulation (in the Atlantic, Pacific, and Indian Oceans), equatorial waves, part of the large-scale ocean circulation, features such as gyres directly driven by persistent or repeated patterns in the wind, often in conjunction with geometric constraints, e.g. many of the circulation features in the Mediterranean Sea with scales >100 km

olution of 25 km is adequate for most mesoscale phenomena. For both wind speed and SST the SMMR on SEASAT (1-m diameter antenna) yielded poor results in areas of sun glint and within 600 km of land (Lipes, 1982). Some work has also been done on satellite measurement of latent heat fluxes (Liu, 1984) and incident solar radiation at the surface (Gautier, 1981), the two heat fluxes that are usually the largest at the air-sea interface.

The prediction of mesoscale (50 to 500 km) eddies, meandering currents, and frontal positions (phenomena in Class 2) is the subject of the remaining sections of this paper. The prediction of this class of phenomena is one area where altimeter data can play a central role. This is because (1) individual mesoscale eddies and current meanders are often not driven *directly* by the wind or by any other external forcing function, and (2) eddies can persist for more than a year after their initial generation (Lai and Richardson, 1977). Thus, oceanic data are crucial for reliable prediction of individual eddies and current meanders. With sufficient oceanic data, we anticipate that the prediction of these features can be treated as an initial value problem in which the future forcing functions are representative but not accurate on time scales greater than a few days. Without oceanic data input, simulation can be used to predict the statistical properties of features and ensembles, but usually not the evolution and movement of the individual features.

Up until now there has been little work on the prediction of Class 2 phenomena, except for the work on the prediction of mesoscale eddies, using limited-area models, by A. R. Robinson's group at Harvard (Robinson and Haidvogel, 1980; Robinson and Tu, 1982; Miller and Robinson, 1984). However, there is a substantial body of literature on the simulation and ocean dynamics of Class 2 phenomena that is very useful in the design of ocean circulation prediction models (Holland and Lin, 1975; Rhines, 1977; Robinson et al., 1977; Semtner and Mintz, 1977; Holland, 1978, 1982; Semtner and Holland, 1978; McWilliams et al., 1978; McWilliams and Flierl, 1979; Cox, 1979; Holland and Rhines, 1980; Hurlburt and Thompson, 1980, 1982; Lin and Hurlburt, 1981; Schmitz and Holland, 1982; Heburn et al., 1982).

ployed by Sarmiento and Bryan (1982) and Clancy and Pollak (1983).

Thus far only nowcasting of Class 3 phenomena has been discussed. Forecasting of these phenomena is based on the hypothesis that although they are a direct response to the atmospheric forcing functions, the response is slow enough to be insensitive to forecast errors in the daily fluctuations of the atmosphere. This insensitivity should permit forecasts on time scales greater than the few days possible for atmospheric prediction.

Haney (1980) has performed non–eddy-resolving nowcasting and forecasting studies of large-scale ocean anomalies, using a closed rectangular domain covering a major portion of the North Pacific, a region adequately sampled for large-scale anomalies at the time by ships of opportunity (White and Bernstein, 1979). The model included simple mixed-layer physics and ten levels in the vertical with six in the upper 262 m. The model was spun up for 250 years by using climatological forcing. Then four experiments were performed. In the first an observed thermal anomaly was added to the climatologically driven state and the model was integrated for four additional months by using climatological forcing. The four-month forecast was poor, but slightly better than a forecast of persistence. Next, three nowcast experiments (in the sense described earlier) were performed. Each time the model was integrated over four months by using observed forcing functions, which had been averaged for a month. The options were observations or climatology for the winds, the heat fluxes, and the initial state. In the first nowcast experiment, observations were used only for the winds, in the second only for the heat fluxes, and in the third for all three functions. In all three cases the results were quite good in the upper 100 m and much better than persistence or the forecast. Between 100 and 300 m the results were not as good, but better than persistence and better than the forecast, except in the second experiment, where the results were poor. Clearly, additional research is required to determine the usefulness of the nowcast and forecast hypotheses presented for Class 3 phenomena.

Many of these have simulated some features of the ocean circulation with substantial success by using simple models, rectangular domains, and simple steady forcing functions. These successes are an indication of potential predictive skill, but one that is largely unverified at this time. It is noteworthy that no ocean modeling study yet published has included all of the following basic features: (1) resolution sufficient for mesoscale eddies, (2) stratification, (3) realistic coastline, (4) realistic bottom topography, (5) thermodynamics and mixed-layer physics, (6) integration to statistical equilibrium, and (7) a deep ocean basin with dimensions (L) large enough ($L \sim 1000$ km or more) for planetary vorticity advection to be important (that is, $L \gg (V/\beta)^{1/2}$, where V is a characteristic velocity, β is the variation of the Coriolis parameter f with latitude ϕ, $f = 2\omega \sin \phi$, and ω is the angular velocity of the earth's rotation.

Phenomena in Class 3 are a direct response to atmospheric forcing, but on much longer time scales than those in Class 1. Because they are a much more integrated response to the wind, the requirements for temporal resolution and accurate depiction of daily atmospheric fluctuations are not as stringent as in Class 1. In Class 3 "nowcasting" and forecasting may be feasible from new atmospheric forcing functions without new oceanic data.

Class 3 predictions might be accomplished by spinning up the forecast model to the present, using the best historical data available for the forcing functions. The spin-up should be long enough to allow the model to reach statistical equilibrium. Busalacchi et al. (1983) have applied this technique to a simple linear model of the tropical Pacific Ocean, with some success on seasonal and interannual time scales. Preller and Heburn (1983) have shown that a simple model of the western Mediterranean Sea, driven by mean monthly winds from May (1982), can reproduce many of the major persistent features observed with scales greater than 100 km. The addition of altimeter-derived sea-surface elevations accurate on the scales of major ocean basins as well as on mesoscales would reduce the burden on the simulation skill of the model. Relaxation of the model simulation toward observed climatology would also reduce the burden. This is a technique em-

Time and Space Scales for the Prediction of Major Current Systems and Eddies

The U.S. Navy is particularly interested in phenomena that can substantially affect acoustic propagation on tactical space scales up to several hundred kilometers. As a result this paper will focus on the potential for forecasting major current systems, mesoscale eddies, frontal locations, and the mixed layer, all features that have been demonstrated to have an important impact on acoustic propagation (Baer, 1980; Beckerle et al., 1980; Nysen et al., 1978; Lawrence, 1983; Itzikowitz et al., 1983).

A schematic diagram from the report of the TOPEX Science Working Group (1981) is quite instructive. Figure 1 plots the

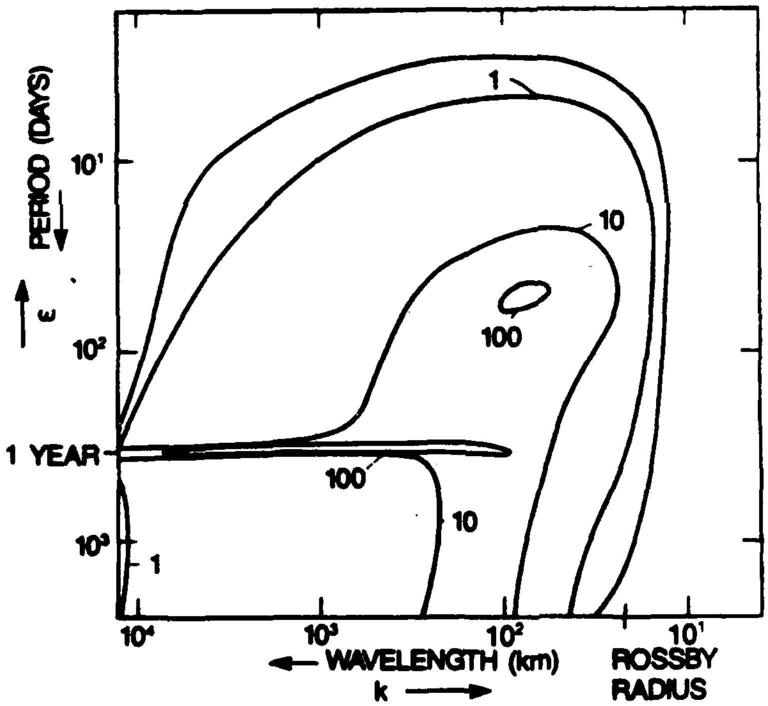

FIGURE 1. Schematic diagram of the time scale versus the space scale for oceanic variability away from boundary layers and contoured in arbitrary units (from the TOPEX Science Working Group, 1981).

amplitude of oceanic variability versus time scale and horizontal length scale. It is representative of the open ocean tens of meters from the surface or bottom and a few hundred kilometers from the equator or coastal boundaries. The peak in variability around sixty days and 100 km associated with Class 2 phenomena implies the need for about 10-km grid resolution in the corresponding numerical ocean circulation forecast models (Grammeltvedt, 1969, Haidvogel et al., 1980). A similar peak for the atmosphere occurs at about six days and 3000 km (Vinnichenko, 1970; Kao and Lee, 1977), indicating that this resolution is dynamically comparable to 300 km in atmospheric models. Atmospheric predictability has received substantial attention (e.g., Lorenz, 1982). Usable predictive skill of about one week is indicated for atmospheric systems, systems dominated by major cyclones, anticyclones, and waves on the jet stream. Comparable predictability studies have not been made for the ocean. However, as noted by Haidvogel and Holloway (1984), predictability studies using simple quasigeostrophic models can be applied to either the ocean (o) or the atmosphere (a) by appropriate scaling, and a reasonable choice of velocity scales ($V_o \sim 10$ cm/s, $V_a \sim 10$ m/s) and length scales ($L_o \sim 100$ km, $L_a \sim 1000$ km) yields an oceanic time scale (L_o/V_o), $O(10\times)$ the atmospheric one. This is consistent with McWilliams and Shen (1980), who suggest $2\pi L_o/V_o \simeq 60$ days as a crude estimate of the predictability time scale for a field of mesoscale ocean eddies. The quasigeostrophic scaling and the observed six- versus sixty-day peak for atmospheric versus open ocean temporal variability at least hint that oceanic forecast skill for Class 2 phenomena may extend about ten times longer than atmospheric predictive skill.

Quite different results have been obtained by Miller and Robinson (1984). They have used a six-layer quasigeostrophic model with a 500-km by 500-km open domain to study the predictability of eddies in the region of the POLYMODE field program in the Atlantic southwest of Bermuda. This is a relatively benign region with no major current systems passing through it. Instead it is populated by mesoscale eddies that are consistent with Figure 1 and that have flow speeds around 20 cm/s and westward propagation speeds of about 6 cm/s. The interior and

the open boundaries of the forecast model were initialized at all levels in the vertical by error-free simulated data taken from an integration of the same model on a larger domain, an integration also used for forecast verification. Atmospheric forcing was omitted. When the open boundary conditions were held fixed in time, Miller and Robinson found that the forecast was superior to persistence for the interior field for only about two days (R. N. Miller, Tulane University, New Orleans, personal communication, 1983) and that errors reached the 50% level in about four days. However, errors remained low for the three-month duration of the experiments, if the open boundary conditions were updated frequently enough (at least every four days in their case). Carter and Robinson (1981) have performed a space-time objective analysis of the depth of the 15°C isotherm (mean depth $\approx$ 600 m) using POLYMODE expendable bathythermographs (XBTs). The analysis was dominated by mesoscale features and showed that a forecast of persistence would yield a linear correlation of .6 after ten days, .3 after twenty days, and $-.1$ after forty days.

The results in the two preceding paragraphs are useful in designing a system for oceanic prediction. The results from Miller and Robinson (1984) do not apply directly to enclosed or semi-enclosed domains or to much larger domains with open boundaries, because in their case the open boundary conditions are much more important than the initial conditions in determining the time scales for predictability. However, their results do emphasize that great care must be exercised with open boundary segments or adjacent data-poor regions (McWilliams and Shen, 1980) because of their potential for extreme impact. Research on the methodology and effects of open boundaries must play an important role in ocean prediction studies, because open or artificially closed boundary segments are a necessary feature of any ocean circulation prediction model that does not cover the entire global ocean.

It should be noted that the Naval tactical scale and the horizontal scale of maximum temporal variability strongly overlap. Furthermore, the energy of the time-varying circulation exceeds the energy of the mean circulation over most of the world ocean

(Wyrtki et al., 1976). At oceanic scales greater than 500 km the temporal variability is relatively weak except for an annual variation (Figure 1). Although large-scale anomalies are significant in some regions and could be detected (White and Bernstein, 1979) and at least to some extent predicted (Haney, 1980), this suggests that the coarse horizontal grids used for atmospheric models are of limited value for ocean forecasting except when the resolved scales of the atmospheric forcing largely determine the scales of the oceanic response, for example in prediction of surface waves (Pierson, 1982) and changes in the mixed layer (Clancy and Pollak, 1983).

Some Obstacles to the Development of a Numerical Ocean Prediction Capability

A list of desirable characteristics for a comprehensive ocean prediction model capable of handling Class 2, Class 3, and certain Class 1 phenomena as described in Table 1 (that is, mixed layers and equatorial and some coastal phenomena with short time scales) might include the following:

1. High horizontal resolution, ~10 km.
2. Mixed-layer physics.
3. High vertical resolution for the mixed-layer physics and for the acoustically important temperature and salinity structure.
4. A limited domain (~1000 km by 1000 km or less) to cover the tactical space scale of naval interest or to provide other tailored services (e.g., for fisheries or ice, oil spill, or other pollutant trajectories) while at the same time minimizing the computation.
5. Initialization from observational data (as in meteorology).
6. Predicted forcing functions on the time scale of their validity, and representative but not accurate forcing functions on longer time scales.

To a large extent this list follows the lead of meteorology, a science with thirty years of experience in numerical prediction. However, a numerical ocean prediction system with all of these

characteristics would encounter serious obstacles:

1. In limited-area models (500 km by 500 km), Miller and Robinson (1984) have found that extensive open boundaries that are poorly known pose the most serious limitation to forecast skill.
2. Computing power places a constraint on the combinations of horizontal and vertical resolution, domain size, and model physics that are feasible (see section on computing requirements).
3. At the very least, forecasts of individual current meanders and eddies will require adequate oceanographic data as input. This is not provided on a regular basis by the sources for subsurface data currently available (see section on data requirements).

Up until now, limitations in computing power have forced serious compromises on eddy-resolving ocean models. For a model with 10-km grid resolution, there has been little choice but to confront problems with artificial boundaries, except possibly in semienclosed seas such as the Mediterranean. Furthermore, forecasting with real data has been limited to situations where major field programs such as POLYMODE have provided adequate oceanographic data.

Using a barotropic model in a region that is relatively simple and homogeneous and has well-known statistics, Robinson and Tu (1982) have found that an optimal estimation combination of persistent and statistically forecast boundary conditions can substantially reduce the error growth rate compared to either alone. Embedding limited-area models in non–eddy-resolving basin-scale models is another possibility, but one not very promising in view of the results from Miller and Robinson (1984) and McWilliams and Shen (1980). A future possibility that bears investigation is that of embedding limited-area models with better physics, higher horizontal or vertical resolution in simpler eddy-resolving basin-scale models, or both. This approach has enjoyed significant success in short-range atmospheric forecasts (Miyakoda and Rosati, 1977), but in situations where data pro-

vide at least marginal resolution of the primary features at all levels in the vertical.

The executive summary of the U.S. Navy–sponsored Ocean Prediction Workshop (Mooers et al., 1982) states that "the needed capability of highest priority is a *portable, full water column, limited area, several-day to several-week* prediction system." In the remainder of this paper we will discuss an alternate approach that was not considered in the *Proceedings of the Ocean Prediction Workshop*, but is capable of overcoming the serious problems of open boundaries, computing power, and data input within the next ten years, and meeting the description of a comprehensive ocean model treating Class 2, Class 3, and certain Class 1 phenomena (mixed layers and equatorial and some coastal processes with short time scales) listed in Table 1. The emphasis will be on the treatment of Class 2 phenomena, such as meandering currents and eddies, because they are the most problematic in terms of horizontal resolution, data acquisition, and data assimilation, and because satellite altimeter data should have the greatest impact on this class. In designing the predictive system, only elements that are clearly necessary and feasible within the next decade will be considered. This does not exclude the potential value of other elements. Of necessity some ideas are included that have not been adequately tested and require additional research.

A Cost-Effective Design for Numerical Ocean Prediction Models

There are two basic approaches that have been used in ocean model design. We will call these the *ocean physics* approach and the *ocean dynamics* approach, approaches that have counterparts applicable in almost any field of science. The ocean physics approach (1) concentrates on ocean physics more than ocean dynamics in designing the model, (2) makes the physics and geometry of the model as realistic as possible, and (3) assumes that with good physics the appropriate ocean dynamics will be present automatically, including some that might not have been an-

ticipated. The ocean dynamics approach (1) concentrates on ocean dynamics more than ocean physics in designing the model, (2) designs a model as simple and efficient (cost-effective) as possible while retaining the ability to represent the desired ocean phenomena, and (3) relies on investigation and understanding of ocean dynamics for successful application. Both the ocean physics and the ocean dynamics approaches require validation studies to ensure that the desired phenomena are adequately represented.

As will be shown in the section on computing requirements, the differences in the computational resources needed for application of these two approaches are dramatic, enough so to demand the use of the ocean dynamics approach for at least the next decade. Even when they are computationally tractable, the complicated models resulting from the ocean physics approach tend to be cumbersome to analyze and understand because of the large computational resources required for each experiment and because of the large number of factors affecting the results. Furthermore, as the complication of the model is increased, along with the potential for greater realism, there can be increased potential for pathological behavior, particularly when a number of parameterized processes are included. Thus it is logical to start with the ocean dynamics approach and build toward more complicated models as resources and understanding permit, starting with more realistic models of semienclosed seas or limited-area models embedded in simpler basin-scale models. Even these applications of an eddy-resolving model derived from the ocean physics approach are a strain on current computer capability, as can be seen from the later discussion of computing requirements.

In the following paragraphs, the ocean dynamics approach is used to design a cost-effective numerical ocean prediction system for naval application. The thermal structure is the output from ocean prediction models that is currently of greatest interest to the Navy. Its mesoscale variability is determined primarily by turbulent mixing and by the horizontal and vertical flow fields associated with major current systems, eddies, oceanic fronts, and, particularly near the equator and coastal

boundaries, by baroclinic waves and wind-driven upwelling and downwelling. High *vertical* resolution (a few meters in the upper ocean) is desired for mixed-layer modeling and for the thermal field output for naval operations. In contrast, surprisingly good simulations of major current systems and eddies have been obtained by using as little as a single vertical mode (e.g., Hurlburt and Thompson, 1980, 1982). High *horizontal* resolution (~10 km) is especially important for these simulations.

Great savings can thus be obtained by separating the turbulent thermodynamic problem from the circulation problem as much as possible, keeping in mind how the two interact. The changes in the thermal field resulting from mixing are communicated to the circulation field primarily through the thermal wind relation. The circulation field is communicated to the thermal structure through the horizontal and vertical flow fields.

Consequently, we have adopted a strategy for developing cost-effective ocean prediction models for the Navy based on partial separation of the hydrodynamic and thermodynamic processes. Dynamic ocean circulation models have been developed that include only a small number of layers and incorporate fairly crude mixed-layer physics. In general, two active layers is the minimum to permit coexistence of the pycnocline and topography and to allow the possibility of baroclinic instability. Also, most of the energy in the ocean is found in the two lowest vertical modes, the barotropic and the first baroclinic (Pochapsky, 1976; McWilliams, 1976; Richman et al., 1977; Flierl, 1978; Bernstein and White, 1974). Schmitz and Holland (1982) suggest that three or more layers may be necessary to model the North Atlantic. For operational use we suggest a minimum of three layers with linear stratification in the central layer, but this is a topic for additional research, as is the optimum representation of the vertical structure. The horizontal resolution should be sufficient to resolve major currents, eddies, and topographic features. These circulation models then supply vertical and horizontal advection information to an $N \times$ 1-D model that consists of multiple (N) applications of a one-dimensional (1-D) model on a suitable grid. The $N \times$ 1-D model has high vertical resolution and a more

sophisticated representation of the turbulent thermodynamic processes, processes important in forecasting the oceanic mixed layer in the upper 100 m. The $N \times$ 1-D model would provide the thermal structure forecast with high vertical resolution. To interface with the $N \times$ 1-D model, the layer-depth-averaged velocities from the circulation model can be augmented by a perturbation circulation patterned after Thompson (1974). In the perturbation circulation the velocities and stresses are matched at each layer boundary to provide dynamically consistent smooth vertical profiles of the three velocity components, without interpolation. This calculation includes the effects of horizontal density gradients, vertical friction and rotation to account for dynamic features such as gravitational circulation, and Ekman drift, pumping, and suction.

Another advantage of the partial decoupling of the turbulent thermodynamic and the hydrodynamic predictions is the one-dimensional nature of the $N \times$ 1-D model. Since each vertical profile is predicted independently, the horizontal distribution of the grid points is much more flexible in both coverage and spacing. The horizontal resolution of the $N \times$ 1-D model should be sufficient to represent the forecast phenomena, but it is not dictated by numerics or dynamics. Thus, for a given feature, the grid spacing can be two to four times greater than in a circulation model. Furthermore, different sources for flow fields can be used by different regions of the same $N \times$ 1-D model. An $N \times$ 1-D model from NORDA designated TOPS (Thermodynamic Ocean Prediction System) is already in operational use at the Fleet Numerical Oceanography Center (Clancy and Martin, 1981; Clancy and Pollak, 1983). Circulation models are under development but have not yet been tested operationally. So far, they have been evaluated primarily by investigating simulation skill, ocean dynamic properties, and sensitivity to variations in model parameters, physics, geometry, resolution, forcing functions, and initial data. Studies of predictability and predictive skill are also necessary. As noted earlier, some work on these topics has been done for open-ocean limited-area models (Miller and Robinson, 1984).

Data Requirements, Availability, and Assimilation

The Inadequate Availability of In Situ Data for Eddy-Resolving Ocean Forecasting

Atmospheric forecast models are initialized from observations that have been analyzed and dynamically balanced at all vertical levels. Often, a previous forecast is the first guess for the analysis used as the initial state. The principal object is to forecast waves and eddies with scales of a few thousand kilometers. These scales are marginally to adequately resolved by the observations. The initial state is the primary input data upon which the forecast normally depends, except near the surface.

With a few exceptions (Haney, 1980; Clancy and Martin, 1981; Carter and Robinson, 1981; Ocean Tomography Group, 1982), the approach used in meteorology of initializing a model from observed data at all vertical levels is not feasible in oceanography because the subsurface observational resolution in space-time is much coarser, and the spatial scales of important ocean currents and eddies are much smaller, 0(100 km).

The Fleet Numerical Oceanography Center receives only about two hundred XBT reports a day for the upper kilometer of the global ocean (Bodie and Petit, 1982). However, seven thousand such reports a day are required to cover the global ocean with a 40-km grid once every thirty days (roughly equivalent to every three days in the atmosphere). McWilliams (1982) suggests 25-km resolution for mesoscale features. White and Bernstein (1979) suggest 50 km for mesoscale eddies in the western Pacific, but tolerate large errors. In any case, whether the instrumentation is XBTs, air-dropped XBTs (AXBTs), or satellite-tracked drifters, and whether deployment is by ship or by aircraft, global coverage with adequate space-time resolution for the prediction of mesoscale ocean features, based on conventional subsurface data, is financially, logistically, and politically unattractive, and we must anticipate that adequate sampling with these methods will be limited in coverage. If the data are limited in coverage, then boundary information must be available every few days (not every thirty) if we are to perform even nowcasts

and short-range forecasts of a few days (Miller and Robinson, 1984).

Acoustic tomography is a promising new approach to subsurface ocean measurement that may permit useful coverage and resolution, because the number of vertical profiles increases quadratically rather than linearly with the number of deployments (Munk and Wunsch, 1979, 1982a,b; The Ocean Tomography Group, 1982). However, Munk and Wunsch (1982a) do not suggest that eddy-resolving arrays will be commonplace or that they will cover a substantial portion of the global ocean by the 1990s. They do propose some non–eddy-resolving arrays covering a 2500-km scale. They also note the important constraint that altimeter data can provide for the tomographic inversion problem.

As discussed below, the subsurface data now routinely available are insufficient to define initial states that would provide useful forecasts of mesoscale features, such as meandering currents and eddies, regardless of the methodology used for data analysis and assimilation. Assimilation of extremely sparse subsurface data by an eddy-resolving forecast model could even do more harm than good. The oceanic subsurface data are so sparse that in many cases the deviations of the data points from the initial guess could simply define spurious eddies with scales determined by the influence function of the analysis scheme. eddies that could persist in a several-month forecast. For example, sparse observations of the Gulf Stream could result in large-amplitude eddies in the analysis because the observations were insufficient to define a coherent and narrow meandering current.

Another problem with an inadequate initial state is that some of the forecast changes would represent model spin-up of dynamic features compatible with the physics and geometry of the model, not evolution of the ocean circulation. For example, if a forecast model resolved the Gulf Stream, but the initial state did not, the model would probably predict a narrowing and acceleration of the Gulf Stream, an event that did not occur in the ocean. It is essential that both the model and the initial state

adequately resolve the phenomena of interest in the forecast. However, the circulation model needs horizontal resolution two to four times finer than required for adequate representation by the data, in order (1) to allow accurate numerical integration (Grammeltvedt, 1969; Haidvogel et al., 1980; Robinson and Haidvogel, 1980) and (2) to minimize artificial damping of important scales of motion and associated nonlinear interactions by scale-selective parameterizations of subgrid-scale horizontal mixing (Holland, 1978). Even with adequate data, if the initial state, the atmospheric forcing, and the model are independent factors in the forecast, it is inevitable that model spin-up will make some contribution to the changes forecast by the model, a phenomenon that also occurs in numerical weather prediction and is known as the drift toward model climatology. This drift can result from both inadequate specification of the initial state and from differences between real and model climatology.

Even though subsurface data are generally sparse, where they are available with sufficient coverage and density to define mesoscale features (nowhere at present), they should be used in eddy-resolving forecast models, particularly if they are available on a regular basis and are sufficient to define space-time correlation functions (see Bretherton et al., 1976; Carter and Robinson, 1981). Furthermore, subsurface data must play a crucial role in the local and regional validation of forecast models.

Conversion of Surface into Subsurface Data by Ocean Circulation Models and the Unique Role of Altimeter Data

The preceding subsection has indicated that if forecasts of individual current meanders and eddies are forced to rely on in situ data alone, then the forecasts will at best be limited in coverage and restricted to a short range, because of the limited regions that can be adequately sampled. This subsection considers the potential for ocean forecasting, based on observations from satellites that have nearly *global* coverage, but only at the surface. Satellites and atmospheric models provide the only clear prospects for fields with global coverage that are useful operationally as initial data or forcing functions for ocean forecasts of

meandering currents, eddies, and frontal locations. Satellites provide good prospects for well-observed fields of sea-surface elevation, surface wind stress, sea-surface temperature, and surface heat flux that could be used in ocean prediction.

With the atmospheric models and the satellite data, there is good potential for well-observed fields at the surface, which are useful as input to ocean circulation models, but these do not provide subsurface data. At best, subsurface fields are adequately known only in the mean plus a mean annual variation, except possibly in limited areas. If a forecast model is to rely on data from satellites and atmospheric models, then well-observed surface information must be converted into information about the internal structure of the ocean, a burden that might logically be placed on mixed-layer models for the mixed layer and on ocean circulation models for subsurface information about current systems, eddies, and fronts. So far this is an unproven capability and an important topic for research. However, there are some good hints that this is feasible.

One important hint is the small number of modes required to represent the vertical structure of the ocean (Pochapsky, 1976; McWilliams, 1976; Richman et al., 1977; Flierl, 1978), a point corroborated by Cheney (1982), who has shown the close relationship between the surface dynamic height and the depth of the 15°C isotherm in the Sargasso Sea. This point is illustrated by a two-layer reduced-gravity model that consists of a single internal vertical mode, the simplest ocean circulation model with potential usefulness in simulation and prediction. The model contains an active upper layer and a lower layer that is infinitely deep and at rest. The interface between the layers represents the pycnocline, the sharp change in density with depth that occurs over most of the world ocean.

One notable feature of this model is its capability for initialization by altimeter data alone, except near the equator where knowledge of the wind stress is important for initialization in addition to forcing. A second feature is its one-to-one correspondence between the variations in the sea-surface elevation related to ocean currents and the variations in the depth of the pycnocline, and a third feature is its remarkable ability to sim-

ulate certain ocean phenomena. This ability has been demonstrated for a variety of phenomena in several different regions, for example, the equatorial Pacific (Kindle, 1979; Busalacchi and O'Brien, 1980; Busalacchi et al., 1983), the Indian Ocean (Cane, 1980), the Somali Current (Lin and Hurlburt, 1981), the Gulf of Mexico (Hurlburt and Thompson, 1980, 1982), ocean response to a hurricane (O'Brien and Reid, 1967; Chang and Anthes, 1978; Price, 1981), the Gulf of Guinea upwelling (Adamec and O'Brien, 1978), the Alboran Sea (Preller and Hurlburt, 1982) and the western Mediterranean Sea (Preller and Heburn, 1983). (A few of these models have included more than one internal vertical mode or mixed-layer physics.) The preceding references and the special compatibility with altimeter data offer hints that a reduced-gravity model with a single vertical mode may be able to forecast a substantial part of the potentially predictable oceanic variability associated with major current systems and mesoscale eddies.

However, with only a single (internal) vertical mode, reduced gravity models cannot be recommended for general use as operational eddy-resolving forecast models, because they do not account for the potentially important effects of topography and baroclinic instability. The simplest ocean model that can include these effects is a two-active-layer model with an internal (baroclinic) mode and an external (barotropic) mode, the latter representing the depth-independent flow. The importance of having at least two vertical modes for the Gulf Stream has been demonstrated by the work of Holland and Lin (1975), Rhines (1977), Semtner and Holland (1978), and Hurlburt and Thompson (1984), and for the Antarctic Circumpolar Current by McWilliams et al. (1978). Schmitz and Holland (1982) suggest that three or more layers may be required for the North Atlantic. It is also noteworthy that the sea-surface elevation in layered models is balanced by the depth-averaged geostrophic velocity in the uppermost layer, while the oceanic current-related sea-surface elevation is balanced by the geostrophic component of surface currents. Thus the models tend to underestimate the amplitude of the current-related sea-surface elevation, a situation that should be taken into account when one is using altimeter data in ocean models.

Munk and Wunsch (1982a) corroborate the severe limitations of conventional in situ data (and the promise of acoustic tomography) for describing the world ocean. In addition, they cite the importance of satellite data at the surface and the importance of models in converting these surface data into subsurface information.

Simulation Skill of a Low-Vertical Resolution Model for the Gulf of Mexico

As an example, Figure 2 illustrates the simulation skill of a model for the Gulf of Mexico with two active layers, realistic coastline geometry and bottom topography, and horizontal resolution sufficient for major current systems and eddies. Surprisingly, no eddy-resolving ocean modeling study published until now has included all of these features in a deep ocean basin where planetary vorticity advection was important and the model was integrated to statistical equilibrium. This calculation was performed by A. Wallcraft of JAYCOR, Alexandria, VA (personal communication, 1982) using the model of Hurlburt and Thompson (1980). The model's ability to handle detailed coastline geometry was Wallcraft's addition. The model was driven from rest to statistical equilibrium solely by a *steady* inflow through the Yucatan Straits between Cuba and Mexico, which was compensated by outflow through the Florida Straits. The model parameters are:

Upper/lower layer inflow transport = 26/4 m^3/s
Horizontal eddy viscosity $A = 300$ m^2/s
The Coriolis parameter at the southern boundary $f_o = 5 \times 10^{-5}$ s^{-1}
Gravitational acceleration $g = 980$ cm/s^2
Reduced gravity $g' = 3(H_1 + H_2)/H_2$ cm/s^2
Reference thicknesses of the layers $H_1 = 200$ m, $H_2 = 3400$ m, $\beta = df/dy = 2 \times 10^{-13}$ cm^{-1} s^{-1}
Surface and interfacial stresses = 0
Stress coefficient for quadratic bottom stress $C_B = 2 \times 10^{-3}$
Horizontal grid increments for each variable $\Delta x = \Delta y = 25$ km

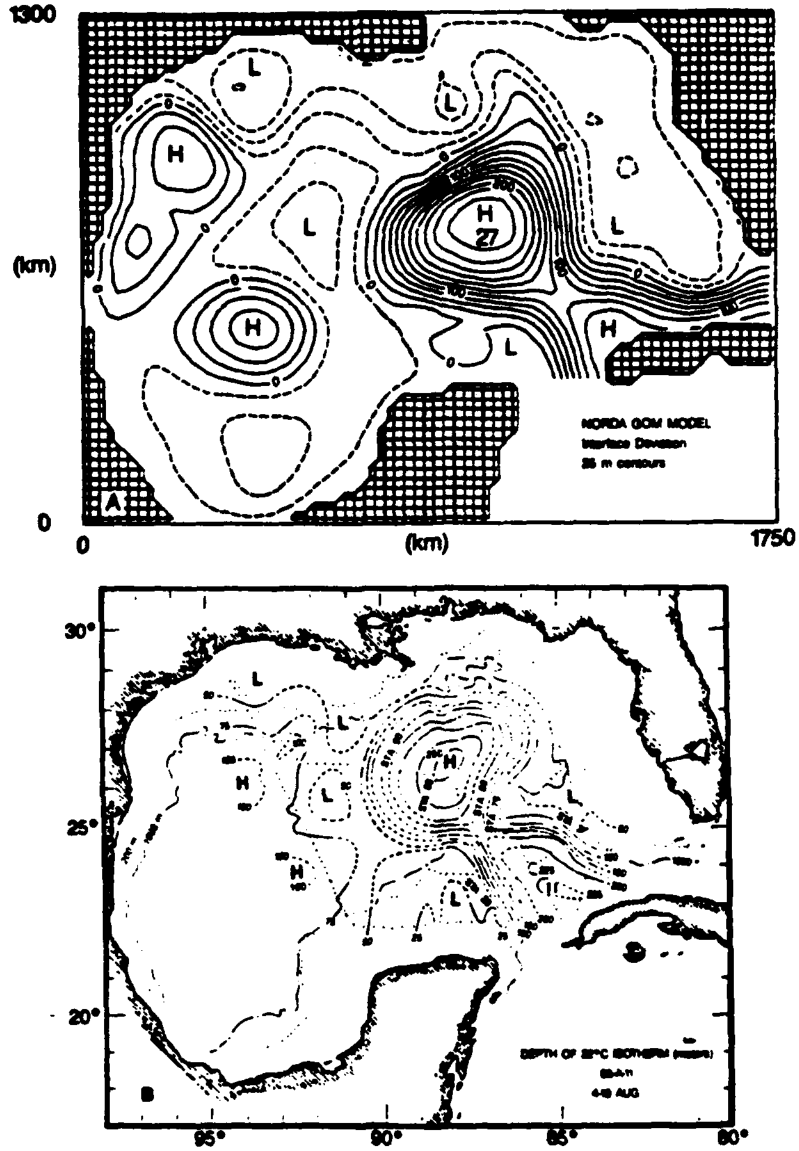

FIGURE 2. (*a*) Instantaneous view of the interface deviation in a two-layer simulation of the Gulf of Mexico driven from rest to statistical equilibrium solely by inflow through the Yucatan Straits. The contour interval is 25 m, with solid contours representing downward deviations. (*b*) Depth of the 22°C isothermal surface, 4–18 August 1966 (*Alaminos* cruise 66-A-11), from Leipper (1970). The contour interval is 25 m.

Time step Δt = 1 h
Inflow spin-up time constant = thirty days
Minimum depth of the bottom topography = 500 m

Figure 2 compares "instantaneous" upper ocean flow patterns (*a*) from the numerical model and (*b*) from observations by Leipper (1970). The Loop Current is the major current system depicted. At this point it is about to shed an eddy. The Loop Current is observed to penetrate the Gulf of Mexico, bend westward, and shed an eddy with a period of approximately one year. This "annual" cycle was long thought to be due tc seasonal variations in the flow through the Yucatan Straits (Cochrane, 1965). However, the model Loop Current exhibits an approximately annual eddy-shedding period when the inflow is steady, contradicting the earlier hypothesis. Although time variations are not essential, they can still play a significant role in the eddy shedding (Hurlburt and Thompson, 1980). The model Loop Current also spontaneously shed eddies with realistic diameters, amplitudes, and westward propagation speeds. The dynamic basis for the agreement between the observations and a circulation model with low vertical resolution is discussed by Hurlburt and Thompson (1980, 1982).

After an eddy is shed by the Loop Current, it propagates westward (Figure 3*a*). In this case there was spontaneous development of a counter-rotating vortex pair when the eddy reached the western gulf (Figure 3*b*), a structure repeatedly observed in that region (Figure 4). The roles of the wind and the eddies from the Loop Current in the formation of this structure have been a matter of some controversy (Merrell and Morrison, 1981). Wind forcing was omitted from the numerical experiment shown in Figures 2 and 3. Although wind forcing is not essential, a significant role for it has not been ruled out.

Strategy for the Assimilation of Surface Data in Ocean Circulation Models

We have already noted the simulation skill of models with low vertical resolution and the one-to-one correspondence between the sea-surface elevation and the internal structure in a model

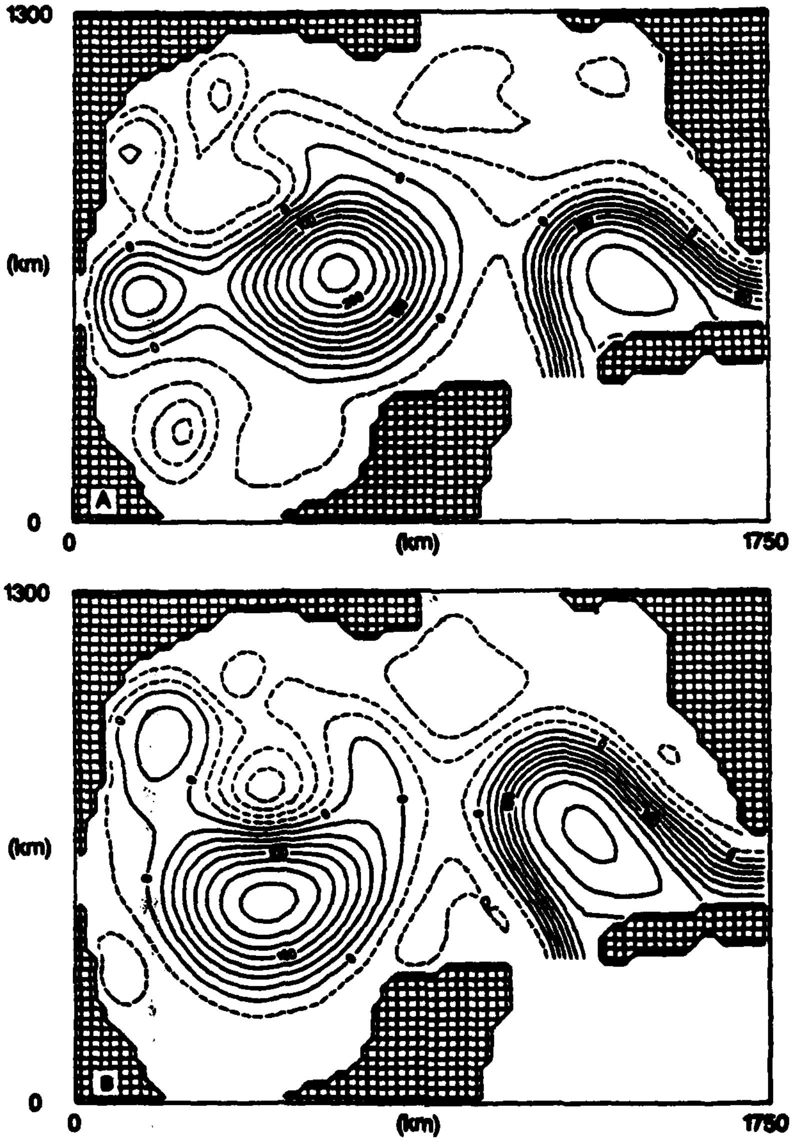

FIGURE 3. *(a)* Interface deviation from the Gulf of Mexico simulation at day 1970 after an eddy has separated from the model Loop Current and propagated westward. *(b)* Ninety days later the major anticyclonic eddy at day 1970 has developed into a counter-rotating vortex pair in the western gulf. The cyclonic vortex is to the north and the anticyclonic to the south. The contour interval is 25 m.

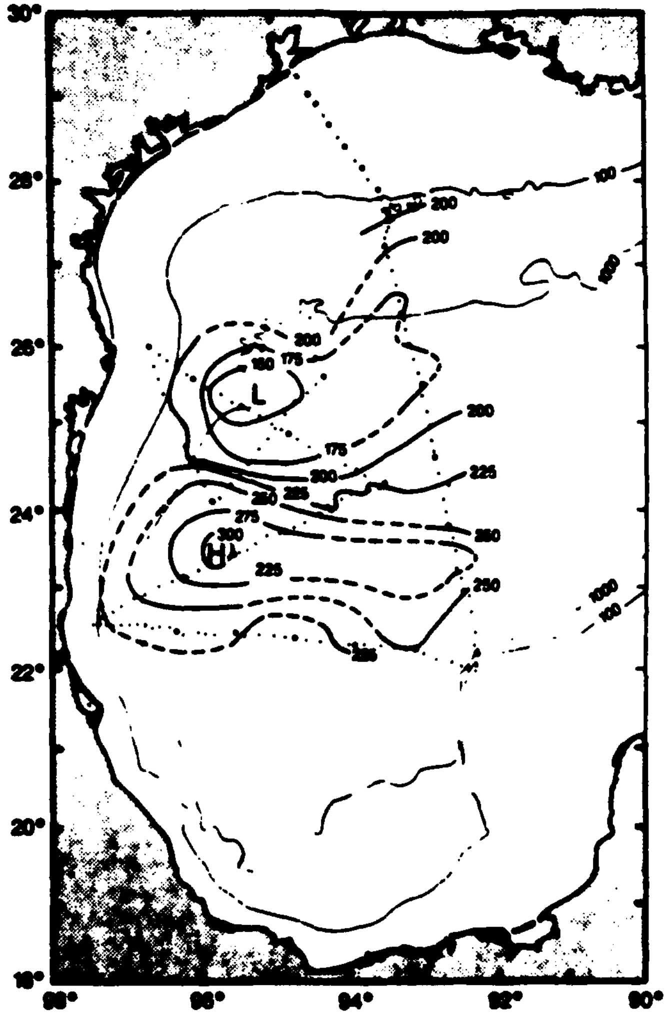

FIGURE 4. Counter-rotating vortex pair in the western Gulf of Mexico as shown by the depth of the 15°C isotherm (in meters), observed in April 1978. The cyclonic vortex is to the north and the anticyclonic to the south. The contour interval is 25 m (from Merrell and Morrison, 1981).

that represents the single vertical mode explaining the majority of the oceanic variance. In view of this and the discussion earlier in this section, it seems preferable to rely on the simulation skill of a more realistic forecast model to distribute the potentially abundant surface information among the small number of vertical modes than to assimilate subsurface in situ data in regions where they are too sparse to adequately define mesoscale features.

Thus the following procedure is recommended: The ocean circulation model for Class 2 and Class 3 phenomena (Table 1) should be spun up to statistical equilibrium by using the best historical data available as forcing functions. This would provide the initial state for ocean forecasting. The initial state could be updated by integrating the model forward in time as new data for the forcing functions arrived. Once they became available, scatterometer-derived wind stress data and the current-related component of the sea-surface elevation from altimeter data could be introduced as forcing functions. This should greatly improve the accuracy of the initial state for the ocean forecast, and for the first time make it possible to predict the evolution of individual current meanders and eddies on a global basis. Introduction of the altimeter data would require special care to avoid serious unphysical dynamic imbalances in the model. This approach, though attractive, is unproven at this time and is an important topic for research. In regions where adequate subsurface data are available, they should, of course, be used.

Resolution Requirements for Altimeter and Scatterometer Data

The horizontal and temporal resolution required for the forcing functions is dictated primarily by the space and time scales of the atmosphere. Thus, scatterometer-derived wind stress data would be needed on a daily basis to resolve the evolution of atmospheric storm systems. The spatial resolution of the wind stress data should be sufficient (~50 km) to resolve the wind stress curl associated with atmospheric cyclones, anticyclones, and fronts. Winds as close to coastlines as possible are highly desirable. In these regions horizontal resolution should be 20 km or better. Since a satellite scatterometer with an orbit altitude

of about 850 km has about a 1500-km swath width (with gaps), a single satellite in conjunction with atmospheric models and the existing data base could meet these requirements adequately (Satellite Surface Stress Working Group, 1982).

Cheney and Marsh (1981) have already demonstrated the ability of the SEASAT altimeter to detect the Gulf Stream and mesoscale eddies when using either repeat tracks or a geoid, and Cheney et al. (1983) have used nine sets of three-day repeat tracks from SEASAT to produce a global map depicting the root-mean-square (RMS) mesoscale variability of the sea-surface elevation during September and October 1978. Tapley et al. (1982) and Wunsch and Gaposchkin (1980) review the problem of obtaining accurate measurements of current-related variations in the sea-surface elevation from a satellite altimeter and the success achieved with SEASAT. To be useful in ocean circulation prediction, the altimeter data must, of course, resolve major current systems and eddies in time, amplitude, and horizontal dimension. However, the amplitude dependence on horizontal scale should also be noted. For currents in geostrophic balance,

$$\hat{k} \times f\mathbf{v}_g = -g\nabla\eta$$

where f is the Coriolis parameter, $\mathbf{v}_g$ is the velocity of the geostrophic surface current, g is the acceleration due to gravity, and η is the sea-surface elevation above the geoid related to oceanic surface currents. The maximum velocity V for typical, significant, persistent, mesoscale (~50 to 500 km) features in the ocean ranges from about 10 cm/s to 1 m/s. Up to 2 m/s is not uncommon in the stronger currents. For an altimeter that can usefully measure oceanographic features with a minimum amplitude of η = 10 cm, the minimum radius of an eddy or half-width of a current L with V = 10 cm/s is L = 100 km at 42° latitude and L = 150 km at 27° latitude. For V = 100 cm/s, L = 10 km at 42° latitude, and the Rossby number $R_o = V/fL = 1$. For $R_o \ll 1$ the flow is geostrophically balanced. For $R_o \gg 1$ vortices can develop cyclostrophic balance,

$$\frac{v_\theta^2}{r} = -g\frac{\partial\eta}{\partial r}$$

where v_θ is the tangential velocity and r is the radius of curvature. In this case the amplitude of η associated with the vortex is dependent on v^2 but is nearly independent of the scale of the vortex. However, a velocity scale greater than 2 m/s is required for a signal in the sea-surface elevation greater than 10 cm.

From this we conclude that a satellite altimeter able to measure variations in the sea-surface elevation greater than 5 cm, which are associated with oceanic currents, should provide usable information for the more significant currents and eddies with scales greater than a few tens of kilometers. This accuracy is feasible with current technology (TOPEX Science Working Group, 1981). Altimeter track spacing of about 30 km and at most 50 km at midlatitudes is needed for horizontal resolution of most detectable eddies. Experiments by Kindle et al. (1984) have shown that three ascending or descending tracks with error-free data are sufficient to adequately map an eddy with a nearly circular shape. Repeat intervals up to a month should provide adequate temporal resolution for most mesoscale features (Figure 1), particularly with the aid of predictive models to fill in the temporal gaps. To minimize the time required for altimeter tracks to span a given eddy, the orbit should be chosen so that adjacent tracks are one day apart. This requirement should override any concern about tidal aliasing, since the tides are relatively large-scale phenomena and because removal of the tidal contributions to the sea-surface elevation appears feasible (Schwiderski, 1980; Cartwright and Alcock, 1981; Brown and Hutchinson, 1981; Diamante and Nee, 1981; Mazzega, 1983). However, as noted in some of the preceding references, accurate determination of the tidal phases and amplitudes would be facilitated by at least once having an altimeter in an orbit relatively free of tidal aliases with long periods.

A single satellite in a twenty-day repeat orbit that carried a multibeam altimeter (see Bush et al., 1984, in this issue) could easily meet the preceding requirements. Minimal satisfaction of the requirements could be achieved by using a single satellite with a nadir beam altimeter in a forty-day repeat orbit, if a numerical model was able to bridge the temporal gaps. Because numerical ocean models should have forecasting skill, it is pref-

erable to reduce the temporal resolution rather than the spatial resolution. In the absence of an adequate geoid, it would be necessary to use a mean sea surface, so that only deviations from the mean would be available to the model. In that case the model could obtain the mean from its own or observed climatology. Bandpass filtering could be required to remove short [<0 (10 km)] and long wave (greater than a few thousand kilometers) errors, the scales with the greatest errors (TOPEX Science Working Group, 1981).

Computing Requirements

Once a particular ocean model design has been chosen and the universal need for approximately 10-km grid resolution of ocean currents and eddies has been noted, then there is a simple relationship between basin size and the computer power required. Based on a three-layer version of the circulation model discussed in the section on cost-effective design, Table 2 lists oceanic domains versus computer power required. The Class 7 machines expected on the market in the middle and late 1980s will be the first that are adequate for all major ocean basins.

In view of the large computer power required, possibilities for reducing it merit consideration. The limited utility of a model with low horizontal resolution has already been noted in the section on time and space scales and Figure 1. Three other possibilities are (1) alternate model designs, (2) the use of virtual/auxiliary memory, and (3) the use of nested grids or subdomains of major ocean basins.

Table 3 compares one model (NORDA's) developed by using the ocean dynamics approach (see the beginning of the section on cost-effective design) with two models closer in design to the ocean physics approach (Science Applications, Inc. [SAI] and Dynalysis). The SAI (Roberts et al., 1980) and Dynalysis (Blumberg and Mellor, 1983) models are both multilevel models with a terrain-following σ-coordinate system. Approximately fifteen levels are the minimum required for adequate resolution of the vertical structure and the relatively sophisticated parameterization of the mixed-layer physics. The NORDA model can work

Table 2
Computer Power Required for Modeling Different Ocean Basins[a]

Computer Class	Capacity	Model Resolution	Oceans Modeled
6	~100 megaflops, 3 million words	10-km grid	Bering Sea
		10-km grid	Caribbean Sea
		7.5-km grid	eastern Mediterranean Sea
		10-km grid	Gulf of Mexico
		10-km grid	Sea of Japan
		10-km grid	South China Sea
		7.5- × 5-km grid	western Mediterranean Sea
6½	~300 megaflops, 8 million words	7.5- × 5-km grid	entire Mediterranean Sea
		0.125° grid	North Atlantic Ocean (20°–60°N)
		0.2° grid	Indian Ocean (north of 30°S)
7	~1 gigaflop		
	32 million words	0.1° grid	Indian Ocean
			North and South Atlantic (separately)
			North and South Pacific (separately)
	64 million words	0.1° grid	entire Atlantic Ocean
			entire Pacific Ocean
	128 million words	0.125° grid	world ocean

[a] Requirements are based on a three-layer version of the NORDA ocean circulation model. From estimates by A. Wallcraft. Note that the quoted megaflop rates are sustainable speeds on NORDA ocean models, which are faster than most computer codes; maximum machine speeds are two to four times higher.

Table 3
Estimated Resources Required for a North Atlantic Ocean Forecast by Three Numerical Ocean Models

Model	Vertical Resolution Required	Horizontal Resolution[a]	Computer Memory Required, words	Central Processor Time Required,[b] h	Time Step, min
NORDA	3 layers	1/8° × 1/10°	8.6 M[c]	0.9[c]	60
SAI	15 levels	1/8° × 1/10°	54 M[c]	22[c]	60
Dynalysis	15 levels	1/8° × 1/10°	66 M[d]	65[d]	12[e]
NORDA	3 layers	1/16° × 1/20°	34 M[c]	7[c]	30
SAI	15 levels	1/16° × 1/20°	215 M[c]	175[c]	30
Dynalysis	15 levels	1/16° × 1/20°	265 M[d]	520[d]	6[e]

[a] Horizontal resolution required is ~10 km for the NORDA model, but higher horizontal resolution may be required to resolve certain important topographic features in the other two (see text). Model domain is 20°–60°N, 10°–80°W.

[b] For two-month forecast on two-pipe CYBER 205. The CYBER 205 is used as a standard reference machine; most of these forecasts could not run core-contained on a 205.

[c] A. Wallcraft (JAYCOR, Alexandria, VA), personal communication, 1983.

[d] Time extrapolated from Blumberg and Mellor (1984); memory from Blumberg (Dynalysis of Princeton, Princeton, NJ), personal communication, 1983.

[e] For internal modes, external is 1/60 internal (Blumberg and Mellor, 1984).

with much lower vertical resolution by using natural layers in the oceanic structure and a Lagrangian vertical coordinate in which the layers change thickness and move vertically in response to the ocean circulation and a crude parameterization of vertical mixing.

In the approach discussed in the section on cost-effective design, a circulation model with low vertical resolution fed horizontal and vertical advection information to an $N \times 1$-D mixed-layer model with high vertical resolution and more sophisticated mixed-layer physics. Because the calculations at the individual grid points are independent in the $N \times 1$-D model, the numerics and the dynamics do not dictate horizontal grid resolution finer than required to represent the features of interest, and the grid spacing can be two to four times greater than in the circulation model. Also, open boundaries are not a problem and the coverage and resolution are much more flexible. Furthermore, mixed layers are Class 1 phenomena (Table 1) which are restricted to short-range forecasts. Thus the $N \times 1$-D model can be a relatively inexpensive calculation and is not included in Table 3.

The comparison in Table 3 is based on estimated resources required for a two-month forecast using an eddy-resolving North Atlantic prediction model. Two-month forecasts are appropriate for Class 2 phenomena such as meandering currents and eddies. These three models were partly chosen to facilitate the comparison, because all three have executed smaller computations on the same vector computer, the two-pipe Texas Instruments Advanced Scientific Computer (TI/ASC) at the Naval Research Laboratory in Washington, DC. The TI/ASC times estimated for the North Atlantic were reduced by 1/7.5 to provide estimates for a two-pipe CYBER 205, the most powerful computer currently used for ocean modeling (Geophysical Fluid Dynamics Laboratory, Princeton, NJ; NASA/Goddard, Greenbelt, MD; Fleet Numerical Oceanography Center (one-pipe), Monterey, CA). The nominal execution speeds for the NORDA model are 20 megaflops on the two-pipe TI/ASC, 80 megaflops on a one-pipe CYBER 205, and 150 megaflops on a two-pipe CYBER 205 (A. Wallcraft, personal communication, 1983).

The models are listed at two different resolutions to make two points. (1) The SAI and Dynalysis models require higher horizontal resolution to represent a given topographic feature with the same accuracy as the NORDA model. The topography appears undifferentiated in the equations of the NORDA model, but is differentiated in the equations for the other two; see, for example, Rhines's (1977) discussion of the effects of differentiation on spectrum centroids. (2) With double the horizontal resolution, the NORDA model still requires smaller resources than the other two. The relative merits of increasing horizontal and vertical resolution should, of course, be tested, but on a smaller domain than the North Atlantic. This paper has advocated the former for most Class 2 and Class 3 phenomena listed in Table 1, but high vertical resolution is required when sophisticated mixed-layer physics are included. In any case, the SAI and Dynalysis models appear intractable as eddy-resolving models of the larger ocean basins at least for the next decade. For a given model, the memory requirements depend inversely on the square and the computer time inversely on the cube of the horizontal resolution.

All three models use primitive equations and retain a free surface. The NORDA and SAI models increase the time step permitted by using implicit numerical schemes for at least some of the terms. However, the high degree of implicitization in the SAI model makes it inherently the most complicated and most difficult of the three to modify. The Dynalysis model uses an explicit numerical scheme in the horizontal, but separates the external from the internal modes. This separation permits a much longer time step for the internal modes, because the internal gravity wave speed is much less than the external. The time step limitation in the NORDA model differs from that of a quasi-geostrophic model only by a $1/|f|$ stability criterion imposed by the numerical scheme for the Coriolis force. At the resolution used for the North Atlantic model in Table 3, the quasigeostrophic approximation would have little effect on the computer time required. Although this approximation can be advantageous in some situations, it was not used in the NORDA model because it is not valid near the equator, for large-amplitude topography, large scales ($\gg$1,000 km), or large vertical excursions of the pycnocline. For example, Hurlburt and Thompson (1984) found that the effects of large- and small-amplitude seamounts on the Gulf Stream were quite different.

The use of auxiliary memory and asynchronous buffering has long been a popular practice for atmospheric forecast models and was used in early TI/ASC versions of the Dynalysis ocean model (Blumberg and Mellor, 1981). (However, the times in Table 3 are based on a core-contained version [Blumberg and Mellor, 1984], as for the other two models.) A. Wallcraft has noted (personal communication, 1982) that this procedure is not feasible for ocean prediction models unless the input/output speed in megawords/s for virtual or auxiliary memory is 0.1 to 0.3 times the usable megaflop rate. This assumes spending equal time for model execution and memory swapping input/output. On the CYBER 205 computer, time-dependent ocean models must be core-contained because swapping data in and out of central memory is too slow in relation to the central processor speed, by a factor of about a hundred. Even though this situation may change (for example, by using solid state secondary storage

devices or hierarchical memory systems that effectively provide buffering between disks and main memory), central processor speeds of ~1 gigaflop are still required for the larger ocean basins.

Ocean predictions on subdomains of major ocean basins are the third and superficially most attractive way to reduce the computational power required. As discussed in earlier sections, extensive open boundaries are the primary difficulty with this approach. Open boundaries can be tolerated in situations where most of the interesting phenomena are generated within the domain or in cases where the boundary information required is fairly simple, such as flow through a strait or total transport through the boundary. Thus, semienclosed domains with small open boundary segments or major ocean basins with distant open boundaries are tractable.

In sub–basin-scale domains where open boundaries must admit significant meandering current systems and eddies, the open boundaries become the most serious limitation to data assimilation and forecasting skill, unless accurate surface and subsurface boundary information on the currents and eddies is available for the duration of the forecast (Miller and Robinson, 1984). The requirement for information at the open boundaries becomes even more severe when the role that models must play in assimilating data and performing nowcasts is considered. As noted earlier, the conversion of well-observed surface information into subsurface information by means of circulation models is not an instantaneous process, except in models with a single vertical mode. Thus even if adequate data were available at the surface, errors at the subsurface open boundaries would propagate into the domain during the data assimilation process, degrading the ability to initialize the model and make even short-range forecasts of meandering currents and eddies. This situation is even further aggravated when the open domain of interest moves with time, as expected in many Naval applications. In basin-scale domains, assimilation of altimeter data during the nowcasting phase should help to prevent the spread of errors introduced at artificial boundaries more than a yet-undetermined distance into

the model domain. A small amount of crucially sited in-situ data should also help.

Given a limited-area model, three possible ways to reduce the open boundary problem are (1) frequent (every few days) subsurface sampling on the boundaries (Robinson and Haidvogel, 1980); (2) having a satellite altimeter in a few-day repeat orbit, using the repeat orbits as domain boundaries, and empirically converting the surface into subsurface information; and (3) obtaining boundary information from an eddy-resolving basin-scale model. Data with less temporal resolution are required for the interior. The first method is impractical for wide application within the next decade. The second is untested and does not provide data for the interior of the domain. The results from Miller and Robinson (1984) suggest that the success of the third method would depend strongly on the quality of the boundary conditions from the basin-scale model. In the first two methods, the accuracy of the boundary information at future times is likely to limit the forecasts to a few days, although statistical forecasts of the boundary conditions may aid significantly in some situations (Robinson and Tu, 1982).

Forecasts of up to a few months are potentially permitted by the dynamics of phenomena in Classes 2 and 3 (Table 1), phenomena such as meandering currents and eddies. Forecasts of this duration would be highly advantageous in some Naval applications, since they would greatly facilitate dissemination of information to a fleet, permit advance planning when knowledge of the ocean environment was important, and allow substantial knowledge of the ocean circulation and thermal structure up to a few months after the loss of satellites or other sources of data.

In most real-time circulation model applications to open domains, models with basin-scale domains provide the most practical source of data for initialization and open boundary conditions, conditions required at all vertical levels and for the duration of the forecast. However, if the basin-scale model is to provide useful information, it too must resolve the meandering currents and eddies in the forecast. *Thus we cannot escape the need for high-resolution (~10 km) models with domains covering*

major ocean basins, the need for satellite altimeter and scatterometer data with global coverage, and the need for Class 7 computers to perform the numerical integrations for the forecasts, for spin-up of the subsurface initial state, for model validation studies, and for studies of model dynamics and their relation to the ocean. The subsurface initialization, the model validation studies, and the studies of model dynamics can require multi-year integrations to allow the model to reach statistical equilibrium.

Summary and Conclusions

Within the next decade there is high potential for a global real-time description and prediction capability for oceanic eddies, meandering current systems, and frontal positions on time scales up to a few months (despite atmospheric predictability of only about one week; see Table 1). The critical elements required to realize this potential are (1) adequate data input, (2) adequate computing power, and (3) properly designed and adequately validated ocean models for both data assimilation and prediction.

Highly efficient models with low vertical resolution have demonstrated a remarkable ability to simulate meandering currents and eddies, but a high horizontal resolution (~10 km) is required to resolve them. To avoid serious limitations on data assimilation and predictive skill, it is advantageous to use domains that cover major ocean basins or semienclosed seas where the phenomena of interest are generated within the domain, and where the open boundary segments are either small (such as flow through a strait) or very distant from the region of interest. Circulation models on subdomains of major ocean basins that have extensive open ocean boundaries are extremely dependent on some source like a large-scale model for boundary conditions during both the data assimilation and prediction phases. To provide useful boundary conditions, the large-scale model must also have resolution sufficient for the currents and eddies. To model major ocean basins with high horizontal resolution and low vertical resolution, a Class 7 computer (~1 gigaflop and 32 to 128 million

words) is required. The introduction of Class 7 computers is anticipated in the middle and late 1980s.

Currently, satellites and atmospheric forecast models provide the only real prospects for oceanographic data and forcing functions with *global* coverage and resolution adequate for use in ocean circulation models. For this purpose, the two fields of greatest value, which are observable from satellites, are altimeter-derived sea-surface elevations and scatterometer-derived wind stress. Successful ocean prediction appears feasible without extensive subsurface data acquisition, by using the simulation skill of the model to convert the potentially well-observed fields at the surface into subsurface information. This approach looks more promising than attempting to assimilate the extremely sparse subsurface data, a process likely to do more harm than good. Where eddy-resolving subsurface data with useful coverage are available (nowhere at present), they should, of course, be used, especially if they are available on a regular basis and their statistical properties are well known. In the long term, acoustic tomography shows promise in this area, but we anticipate that subsurface data acquisition adequate for prediction of mesoscale features will, at best, be limited in coverage for at least the next decade. Some subsurface data and major field programs are essential for the local and regional subsurface validation of the forecast models.

The surface-to-subsurface data conversion process would be accomplished by using both the altimeter data and the atmospheric data as forcing functions. Although this is an untested hypothesis at this time and the assimilation of the altimeter data could be troublesome, the potential for surface-to-subsurface conversion is enhanced by noting that (1) a single internal vertical mode explains much of the oceanic variance; (2) in a layered circulation model with a single internal mode there is a one-to-one correspondence between variations in the sea-surface elevation and variations in the depth of the pycnocline; (3) such a model can be initialized by altimeter data alone, except near the equator, where wind stress is necessary for initialization in addition to forcing; and (4) such models have demonstrated a re-

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markable simulation skill in certain situations, although they miss the sometimes important effects of topography and baroclinic instability. These effects require at least one additional vertical mode; we recommend no less than three in an operational forecast model. As discussed in the section on cost-effective design, high vertical resolution can be obtained by coupling the circulation model with low vertical resolution to an $N \times$ 1-D mixed-layer model with high vertical resolution.

Altimeter data are essential for *global* prediction and representation of individual current meanders and eddies. Approximately 5-cm accuracy is needed for variations in the sea-surface elevation related to ocean surface currents. Track spacing of not more than 50 km is required at midlatitudes, but repeat intervals up to a month could probably be tolerated. To minimize the time required to span an eddy, the orbit should be chosen so that adjacent tracks are one day apart. A single satellite with a multibeam altimeter and a 20-day repeat orbit could meet these requirements with ease (see Bush et al., 1984, in this issue). Minimal satisfaction of the requirements could be obtained by using a single satellite with a nadir beam altimeter and a 40-day repeat orbit at ~1000-km altitude, if a numerical prediction model is used to fill in the temporal gaps.

In the absence of altimeter data, a further burden would be placed on the simulation skill of the model. Although some oceanic phenomena are quite directly related to atmospheric or other forcing functions, many current meanders and eddies are not because they can result from flow instabilities and because they can persist for many months. These phenomena could only be simulated in a statistical sense. That is, the circulation model would be limited to forecasting ensembles of eddies and the general character, evolution, and movement of eddies and current meanders in different regions.

In the course of this discussion a number of ideas with potential application to ocean prediction have been encountered. Some ideas that show promise are (1) the use of satellite altimeter and scatterometer data, (2) the conversion of surface into subsurface information, (3) the partial decoupling of the ocean circulation problem from the turbulent thermodynamic mixed-layer

problem, (4) eddy-resolving circulation models with low vertical resolution and basin- or global-scale domains, and (5) Class 7 computers. Some that are not promising (at least within the next decade or more) are (1) eddy-resolving models for major ocean basins with many fixed levels in the vertical, (2) the inclusion of sophisticated mixed-layer physics in eddy-resolving circulation models covering major ocean basins, (3) the assimilation of sparse in-situ data by ocean circulation models, (4) coarse grid, non–eddy-resolving prediction models for the ocean circulation, and (5) sub–basin-scale models with extensive open boundaries, except when they can obtain boundary conditions from an eddy-resolving basin-scale model. Nowcasts and short-range forecasts (a few days) from stand-alone limited-area models appear feasible in regions with adequate subsurface sampling (none at present). The first two ideas are judged not to be promising based only on anticipated computing power within the next decade or more.

Within the next decade the appropriate satellite data, Class 7 computers, and eddy-resolving basin- or global-scale models should become available, and they should be used to form the heart of a global ocean prediction system. In the meantime, alternate methods described in this paper and elsewhere can provide a more limited capability that is applicable in some situations. In particular, forcing functions from atmospheric models should permit useful nowcasting and predictive skill for Class 1 and Class 3 phenomena listed in Table 1 prior to the availability of satellite altimeter and scatterometer data.

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